"Hot Spots" of

Land-Atmosphere Coupling

by the GLACE Team*

One-sentence summary: The regions of the globe where soil moisture variations can affect precipitation are determined, for the first time, by a superior multi-model approach.

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Abstract: Previous estimates of land-atmosphere interaction (the impact of soil moisture on precipitation) have been limited by a severe paucity of relevant observational data and by the model-dependence of the various computational estimates. To counter this limitation, a dozen climate modeling groups have recently performed the same highly-controlled numerical experiment as part of a coordinated intercomparison project. This allows, for the first time ever, a superior multi-model approach to the estimation of the regions on the globe where precipitation is affected by soil moisture anomalies during Northern Hemisphere summer. Such estimation has many potential benefits; it can contribute, for example, to seasonal rainfall prediction efforts.

Atmospheric chaos severely limits the predictability of precipitation on seasonal timescales. Indeed, weather forecasts, which rely heavily on atmospheric initialization, rarely demonstrate skill beyond about a week. Hope for accurate seasonal forecasts lies with simulating atmospheric response to the slowly varying states of the ocean and land surface – components of the Earth system that *can* be predicted weeks to months in advance. A systematic response of the atmosphere to these boundary components would naturally contribute skill to seasonal prediction.

The critical importance of the ocean surface in this regard is well known[1]. Ocean temperature anomalies can be predicted a year or more in advance[2]. Furthermore, the atmosphere responds particularly strongly (and predictably) to ocean temperature anomalies in certain regions – "hot spots" of ocean-atmosphere coupling. The eastern equatorial Pacific is the most famous oceanic hot spot, playing a key role in the El Niño - La Niña cycle[3].

Another potentially useful slow component of the Earth system is soil moisture, which can influence weather through its impact on evaporation and other surface energy fluxes. Soil moisture anomalies can persist for months[4], and though a paucity of observations prevents an unambiguous demonstration of soil moisture impacts on precipitation[5], such impacts are often seen in atmospheric general circulation model (AGCM) studies[6 7]. In fact, some AGCM studies suggest that in continental midlatitudes during summer, oceanic impacts on precipitation are small relative to soil moisture impacts[8].

This suggests a question: Are there specific locations on the Earth's surface for which soil moisture anomalies have an especially significant impact on precipitation? The identification of such hot spots would have tremendous implications for the design of seasonal prediction systems and for the associated development of ground-based and satellite-based soil moisture monitoring strategies, if such impacts are found to be local. In a broader sense, such identification is clearly critical for understanding Earth's climate system and the limits of predictability therein.

While AGCM studies[9 10 11 12] and even numerical weather prediction model studies[13] have addressed this question, published results are based on different experimental designs and reflect distinctive features of different model parameterizations. The coupling question, however, was recently addressed en masse by a dozen AGCM groups[14], all performing the same highly-controlled numerical experiment. The experiments were coordinated by GLACE, the Global Land-Atmosphere Coupling Experiment[15]. Each model contributing to GLACE generated several ensembles of boreal summer (June through August) simulations designed to quantify that model's land-atmosphere coupling strength[16] for that season. By combining the results across these models, we eliminate much of the undesired individual model dependence. We obtain, in effect, a unique result: a multi-model average depiction of the global distribution of land-atmosphere coupling strength. Given the limitations of the observational data, both now and in the foreseeable future, such a multi-model estimate of coupling strength distribution is arguably the best estimate attainable.

Each GLACE participant performed an ensemble of sixteen simulations in which soil moisture varied between the simulations, and another ensemble in which the geographically-varying time series of subsurface soil moisture was forced to be the same across the sixteen simulations[17]. Coupling strength – the degree to which all prescribed boundary conditions affect some atmospheric quantity X – can be estimated[18] for each of the two ensembles with the diagnostic Ω:

$$\Omega = (16\sigma^2_{<X>} - \sigma^2_X) \; / \; 15\,\sigma^2_X \, ,$$

where σ^2_X is the intra-ensemble variance of X and $\sigma^2_{<X>}$ is the corresponding variance of the ensemble-mean time series – the single time series generated by averaging across the 16 ensemble members at each time interval, chosen here to be six days. We are

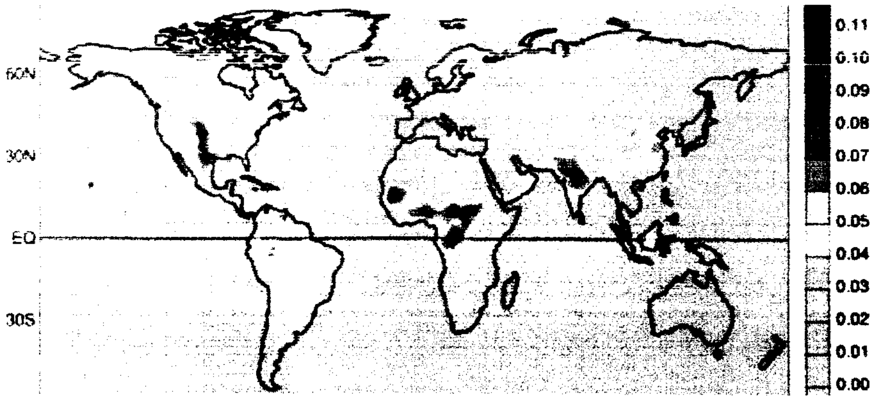

Figure 1. Mean of the land-atmosphere coupling strength diagnostic (the Ω difference, dimensionless) for boreal summer across models participating in GLACE.

The positions of the hot spots are not unexpected[8 19], particularly if the soil moisture influence is presumed to be local rather than remote. In wet climates, for which soil water is plentiful, evaporation is controlled not by soil moisture but by net radiative energy. Thus, in wet climates, precipitation should be insensitive to local soil moisture variations. In dry climates, on the other hand, evaporation rates *are* sensitive to soil moisture but are generally too small to affect precipitation generation; in any case, the atmosphere in dry regions is predisposed to limit precipitation. Only in the transition zones between wet and dry climates, where the atmosphere is amenable to precipitation generation (in particular, where boundary layer moisture can trigger moist convection[20]) and where evaporation is suitably high but still sensitive to soil moisture, can we expect soil moisture to influence precipitation. The major hot spots shown lie mainly in such transition zones.

interested, of course, in precipitation; to reduce noise, though, we take X to be the natural logarithm of the precipitation. Performing statistics on the logarithms of precipitation is a common practice in hydrology and meteorology, since unmodified precipitation distributions tend to be highly skewed.

A study of the equation shows that outside of sampling error, Ω should vary from 0 to 1, with higher values implying a higher impact of the atmosphere's boundary conditions on precipitation. To isolate soil moisture's impact on precipitation from that of the other forcings, such as time-varying ocean temperatures, we compute the difference in the Ω values between the two ensembles. In simple terms, this Ω difference describes the fraction of the precipitation variance explained by variations in soil moisture.

Figure 1 shows the global map of the coupling strength diagnostic – the Ω difference – averaged across all of the participating models in GLACE. Several hot spots appear, most notably the central Great Plains of North America, the Sahel, equatorial Africa, and India. Less intense hot spots appear in South America, central Asia, and China.

[7] Dirmeyer, P. A., J. Climate, 13, 2900-2922, 2000.

[8] Koster et al., J. Hydrometeor., 1, 26-46, 2000.

[9] Douville, H., and F. Chauvin, Climate Dynamics, 16, 719-736, 2000.

[10] Dirmeyer, P. A., J. Hydrometeorol., 4, 329-344, 2001.

[11] Koster, R., and M. Suarez, J. Hydrometeror., 4, 408-423, 2003.

[12] Schlosser, C. A. , and P. C. D. Milly, J. Hydrometeor., 3, 483-501, 2002.

[13] Beljaars, A. C. M., P. Viterbo, M. J. Miller, and A. K. Betts, Month. Weather Rev., 124, 362-383, 1996.

[14] The participating atmospheric general circulation models are from the following groups: (1) Bureau of Meteorology Research Centre, Australia (BMRC); (2) The Canadian Center for Climate Modeling and Analysis, Canada (CCCma); (3) Center for Climate System Research, University of Tokyo and National Institute for Environmental Studies, Japan (CCSR/NIES); (4) Center for Ocean-Land-Atmosphere Studies, United States (COLA); (5) Commonwealth Scientific & Industrial Research Organization, Australia (CSIRO); (6) NASA/Goddard Space Flight Center Laboratory for Atmospheres, Climate and Radiation Branch, United States (GEOS); (7) Geophysical Fluid Dynamics Laboratory, United States (GFDL); (8) Hadley Center, United Kingdom (HadAM3); (9) National Center for Atmospheric Research, United States (NCAR); (10) National Center for Environmental Prediction, United States (NCEP); (11) NASA Seasonal-to-Interannual Prediction Project, United States (NSIPP); and (12) University of California, Los Angeles (UCLA).

[15] GLACE is a joint project of the Global Energy and Water Cycle Experiment (GEWEX) Global Land Atmosphere System Study (GLASS) and the Climate Variability Experiment (CLIVAR) Working Group on Seasonal-Interannual Prediction (WGSIP), all under the aegis of the World Climate Research Programme (WCRP).

[16] Coupling strength in this paper refers to the general ability of land surface moisture anomalies – either local or remote – to affect precipitation in a given region. Inferences regarding soil moisture measurement in the indicated hot spots require an assumption of local influence.

[17] The prescribed soil moistures necessarily differed from model to model, since each time series had to be fully consistent with the individual model using it. The prescribed moistures for a given model came, in

One must not assume from the map that all of the GLACE models place hot spots in the regions indicated. There exists extensive inter-model variability in the strength and positioning of the hot spots, a reflection of ongoing uncertainty in the proper way to represent the physical processes defining land-atmosphere coupling strength. Still, despite this variability, certain patterns appear frequently. These are the patterns that survive the averaging process and appear in Figure 1. Each hot spot shown in the figure was produced, with varying magnitudes, by several of the participating models.

The hot spots indicate where a global initialization of soil moisture may enhance precipitation prediction skill, at least during northern hemisphere summer[21]. Under the assumption that the soil moisture impacts are predominantly local, the hot spots indicate where the routine monitoring of soil moisture, with both ground-based and space-based systems, will yield the greatest return in boreal summer seasonal forecasting. The hot spots are, in a sense, land-surface analogues to the ocean's "El Niño hot spot" in the eastern tropical Pacific.

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[1] Wallace et al., J. Geophys. Res., 103, 14241-14260, 1998.

[2] Kirtman, B. P. and P. S. Schopf, J. Climate, 2804-2822, 1998.

[3] Rasmusson, E. M. and T. H. Carpenter, Mon. Wea. Rev., 110, 354-384, 1982.

[4] Vinnikov, K. Ya., and I. B. Yeserkepova, J. Geophys. Res., 101, 7163-7174, 1996.

[5] Historical soil moisture measurements are mostly confined to Asia[22]. Even if global soil moisture fields did exist, using observations to establish that soil moisture affects precipitation is difficult because the other direction of causality is much stronger – precipitation has a first order impact on soil moisture.

[6] Shukla, J., and Y. Mintz, Science, 215, 1498-1501.

fact, from one of the model's simulations in the first, "variable soil moisture" ensemble. For details, see the experiment plan posted on the GLACE website: http://glace.gsfc.nasa.gov/.

[18] Koster et al., J. Hydrometeorology, 3, 363-375, 2002.

[19] Indirect (and thus limited in its own right) observational estimates[23] of the North American hot spot roughly agree with that shown in the figure.

[20] Sud, Y. C., W. C. Chao, and G. K. Walker, J. Arid Environments, 25, 5-18, 1993.

[21] This study has focused on soil moisture effects alone. A number of studies indicate that vegetation properties and processes also have substantial impacts on climate in a number of regions. For example, Charney et al.[24] describe the importance of surface albedo on North American climate, Dickinson and Handerson-Sellers[25] show the impact of deforestation on Amazonian climate, and Xue et al.[26] demonstrate the importance of vegetation processes on East Asian climate. This issue, like the soil moisture issue, is a subject of continuing investigation.

[22] Robock et al., Bull. Amer. Met. Soc., 81, 1281-1299, 2000.

[23] Koster et al., Geophys. Res. Lett., 30, 1241, doi:10.1029/2002GL016571, 2003.

[24] Charney et al., J. Atmos. Sci., 34, 1366-1385, 1977.

[25] Dickinson and Handerson-Sellers, Quart. J. Roy. Meteor. Soc., 114, 439-462, 1988.

[26] Xue et al., J. Geophy. Res., 109, D03105, doi:10.1029/2003JD003556.

Popular Summary

``Hotspots of Land Atmosphere Coupling", by R. Koster, P. Dirmeyer, Z. Guo, and 21 others. (Submitted to *Science*)

A wetter-than-usual soil may lead to higher-than usual evaporation, which in turn may lead to increased precipitation. This soil moisture - precipitation connection, if verified and properly utilized, would contribute significantly to seasonal forecasting efforts. Seasonal forecasters could then take advantage of the fact that initialized soil moisture anomalies can persist for months.

The problem with verifying the soil moisture - precipitation connection with observational data is that the required data on the large scale do not exist and are logistically impossible to obtain. Climatologists have thus relied instead on modeling studies to quantify the connection. These modeling studies have their own limitations, however; most notably, the results can be strongly model dependent.

GLACE is an international intercomparison project designed to quantify the strength of the soil moisture - precipitation connection (the ``coupling strength") across a broad range of atmospheric general circulation models. Through GLACE, we find that the different models do indeed show a broad disparity in coupling strength distribution. GLACE, however, also provides an intriguing result. Despite the intermodel disparity, certain areas of the Earth show a large coupling strength in many models, suggesting that the existence of significant coupling strength in these areas is not so model-dependent. Given the lack of observational data, such a multi-model determination of areas with strong coupling strength is arguably the best estimate of such areas attainable by any method.

To highlight these areas objectively, we average the coupling strength distributions across the twelve models participating in GLACE. The areas that survive the averaging process -- i.e., the areas that are arguably not model-dependent -- lie in the Great Plains of the United States, in the Sahel, and in northern India. Additional regions with lower coupling strength appear in central Asia and just south of the Amazon. If the soil moisture - precipitation connection in nature is mostly local, these ``hotspots" of coupling show where soil moisture measurement with in situ or satellite sensors would provide the most benefit to seasonal forecasts.